

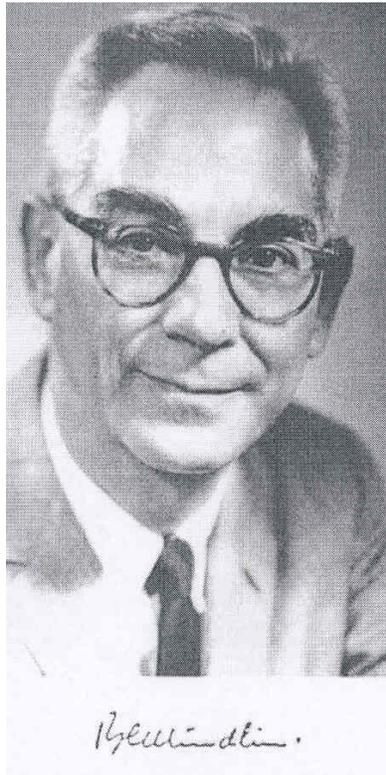
PIEZOELECTRICITY RESEARCH IN IEEE UFFC-S (IN MEMORY OF R. D. MINDLIN)

Yang Jia-shi^{1,2}

⁽¹⁾Institute of Mechanics and Sensing Technology, School of Civil Engineering and Architecture, Central South University, Changsha, Hunan 410083, China)

⁽²⁾Department of Engineering Mechanics, University of Nebraska, Lincoln, NE 68588-0526, USA)

ABSTRACT: This paper provides an overview of the piezoelectricity research in IEEE (Institute of Electrical and Electronics Engineers) UFFC-S (Ultrasonics, Ferroelectrics, and Frequency Control Society). Some mechanics problems are identified. In particular, contributions from Mindlin's school since the 1950s are summarized. The paper is dedicated to the 100th anniversary of the birth of R. D. Mindlin (1906-1987).



Raymond D. Mindlin

I. Introduction

Piezoelectricity is an old subject. It already has a history of over 120 years. During the last few decades the main stream of piezoelectricity research has shifted from the applied physics and acoustics communities to the UFFC-S of the IEEE. The piezoelectricity research in the UFFC-S has been steadily growing since after World War II. It presents many challenging mechanics problems from both materials and devices (structures). However,

research on piezoelectricity in the general mechanics community began rather late in the 1990s from the study of smart structures. Due to lack of common interest, the work done by mechanics researchers on piezoelectricity has been largely ignored by the UFFC-S. The only mechanics group that has been continuously playing an active and significant role in the UFFC-S piezoelectricity research since the 1950s is Mindlin's school which has a tradition characterized by a strong connection between theory and application.

During World War II Mindlin served the government at the Applied Physics Laboratory of the Johns Hopkins University where he lead a team which designed the firing element of the first proximity fuse, a very important device in the war. With the proximity fuse, the shells of anti-aircraft guns do not need to be in contact with an airplane to explode and bring the plane down. The success rate of anti-aircraft guns was then raised by many times. For the development of the proximity fuse Mindlin was awarded the *Presidential Medal for Merit* (see Fig. 1) in 1946, the highest civilian honor at the time which was stopped in the 1950s. After the war Mindlin entered the field of vibrations of piezoelectric crystals (resonators) due to the needs from the Bell Laboratory and the US Army, and never left it. Some of his students (mainly Tiersten, Lee, and Bleustein) continued the research on piezoelectric devices and remain to be an active group in the TUFFC-S. Mindlin received the *National Medal of Science* (see Fig. 2) in 1979, which is the highest civilian honor now for which his contribution to vibrating piezoelectric crystals is partially responsible. In the mechanics community, von Karman seemed to be the only other person who received both of these two medals. Others seem to have none. Mindlin was a member of both the *National Academy of Science* and the *National Academy of Engineering*.



Fig. 1 Presidential Medal for Merit, 1946
“For the development of the proximity fuse, one of the major achievements in the scientific war effort.”



Fig. 2 National Medal of Science, 1979
“For fundamental contributions to applied mechanics, including theory and applications in photoelasticity, package cushioning, piezoelectric oscillators, and ultrahigh frequency vibration”

II. ABOUT THE IEEE UFFC-S

The UFFC-S is one of the smallest of the 45 societies of the IEEE. It has about 2200 members with more than 150 IEEE Fellows. It was founded in the 1980s by combining three previous groups of researchers from frequency control (formed in the 1940s), ultrasonics (formed in the 1950s), and ferroelectrics (formed in the 1960s). The society website is at <http://www.ieee-uffc.org/>.

The UFFC-S has its society journal: the IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control. The society is responsible for the publication and update of the most widely used reference on piezoelectricity: The IEEE Standard on Piezoelectricity.^[1] The society runs three series of annual symposia:

- (i) IEEE International Ultrasonics Symposium;
- (ii) IEEE International Frequency Control Symposium, and
- (iii) IEEE International Symposium on the Applications of Ferroelectrics.

Among its rather broad interest, the society has piezoelectricity and more general electric, magnetic and elastic interactions as one of its emphases. The piezoelectricity research in the society is driven by the following two objectives:

- (i) Growth of new and/or better piezoelectric crystals with desirable properties.
- (ii) Development of new and/or better devices.

For example, during the last decade, on the material side the society contributed to the development of PMN-PT ceramics and single crystals for navy and medical transducers, and langasite single crystals for army telecommunication and missile control applications. The research in the society has a strong connection with the electronics industry, US Navy and Army, and biomedical applications. For devices, the following classification can be made:

- (i) High precision devices like resonators, oscillators, filters and sensors, etc. For these devices materials with low damping and good temperature behavior are needed. Usually single crystals are used.
- (ii) High power devices like certain navy and medical transducers, actuators, and power handling devices like piezoelectric generators and transformers. For these devices high electromechanical coupling is desirable. Both ceramics and single crystals have been used.

III. MECHANICS IN THE IEEE UFFC-S

In the UFFC-S, the use of piezoelectric materials has certain basic features that are different from conventional mechanics consideration. This is responsible for the gross neglect of mechanics type piezoelectricity research by the UFFC-S. For a big portion of the devices of the UFFC-S, the following are true:

- (i) They are resonant devices presenting dynamic problems rather than static problems which are favored by mechanics people because of the relative mathematical ease. Both surface acoustic waves (SAW) and bulk acoustic waves (BAW) are used in these devices.
- (ii) They are usually for information gathering and signal processing where wave frequency and speed are of interest rather than stress and strain for strength and failure consideration.

(iii) For BAW devices, they often operate with the so-called high-frequency modes. Take a plate thickness-shear resonator as an example (see Fig. 3). The high frequency modes, e.g., thickness-shear and thickness-stretch, are those modes whose frequencies are determined by the plate thickness, as compared to the low-frequency modes of extension and flexure in structural engineering whose frequencies are strongly dependent on the length and/or width of the plate.

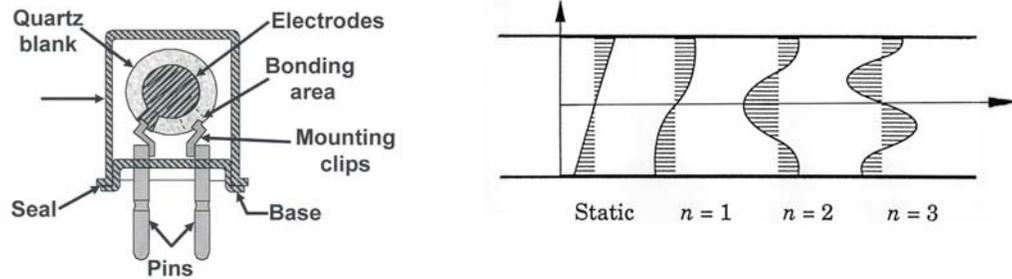


Fig. 3 A plate piezoelectric resonator at its operating thickness-shear modes.

For resonant piezoelectric devices the following issues are of general interest. Most of them are typical mechanics problems:

- (i) Resonant frequencies and modes. This is an eigenvalue problem of the linear theory.
- (ii) Frequency stability versus temperature, force, acceleration and other environmental effects. For this the linear theory for small fields superposed on biasing fields is needed.
- (iii) Behavior near nonlinear resonance including harmonic generation, anisochronism, inter-modulation, etc., and devices for nonlinear signal operation like convolvers. This requires a fully nonlinear theory.
- (iv) Effects of electrodes or a surface layer in general which from a mechanics point of view is the interaction between a body and a thin shell.
- (v) Packaging and mounting.
- (vi) Shock resistance.
- (vii) Measurement of linear and nonlinear material constants of new and old crystals.
- (viii) Vibration of a crystal in contact with a fluid for liquid sensors: fluid-structure interaction.
- (ix) Vibrations of a rotating piezoelectric body for angular rate sensor application.
- (x) Piezoelectric semiconductors for acoustic wave amplifiers and other devices.

Due to the complexity of structural shapes, electrode configurations, and mounting schemes, exact analyses from the three-dimensional equations are rarely possible. Results useful to device design are usually based on the following mechanics tools:

- (i) Lower-dimensional structural theories of beams, plates, and shells. Conventional structural theories for low-frequency extension, bending and torsion are not enough. New theories for high-frequency modes often need to be developed.
- (ii) Finite element numerical methods.

IV. CONTRIBUTION FROM MINDLIN'S SCHOOL

The participation of Mindlin's school in the UFFC-S piezoelectricity research began in the 1950s. In addition to Tiersten's participation in the theoretical part of Ref. [1], the contributions by Mindlin's school can be found in quite a few review articles^[2-6] and books.^[7-15] We discuss a few aspects separately below.

(i) Frequency analysis based on the linear theory of piezoelectricity for small signals. This provides the most basic information of resonant frequencies and mode shapes for design. Frequency analysis began before the computer age when structural theories were the only tools. The shear deformation theory for plates developed by Mindlin in the early 1950s was primarily for the application to thickness-shear plate piezoelectric resonators. A review of structural theories and analyses based on linear piezoelectricity was given in Ref. [2].

However, designs based on linear analyses in general are inadequate because of the frequency stability issue next.

(ii) Frequency stability analysis is based on the linear theory for small fields superposed on a bias, which is a consequence of the fully nonlinear theory. Tiersten systematically developed the theory of nonlinear electroelasticity,^[16] the linear theory for small fields superposed on finite biasing fields^[17] which has to be obtained from the nonlinear theory, and the perturbation integral^[18] for frequency shifts in resonators based on the theory in Ref. [17]. The theories in Refs. [16-18] were summarized in Ref. [19]. Frequency stability analysis has been one of the main research topics since the 1980s. A summary of Tiersten's work can be found in Ref. [20]. A more general review on this can be found in Ref. [3].

(iii) Nonlinear phenomena like nonlinear resonance, harmonic generation and inter-modulation were analyzed based on a cubic theory including all third-order effects of the displacement gradient and electric potential gradient which was derived in Ref. [21].

(iv) Nonlinear theories of piezoelectric semiconductors [22] and analysis of acoustic wave amplifiers [4].

(v) Vibrations of rotating piezoelectric bodies and angular rate sensors [5].

(vi) Analysis of piezoelectric transformers [6].

V. STUDENTS OF R. D. MINDLIN

The list below speaks for itself:

Bleustein, Jeffrey Ph.D. 1965 Yale, Harley & Davidson

Bogdanoff, John Ph.D. 1949 Purdue

Brady, Kevin DES 1964 Bell Labs

Cheng, David Ph.D. 1944 CUNY

Deresiewicz, Herbert Ph.D. 1952 Columbia

Drucker, Daniel Ph.D. 1938 UIUC

Duffy, Jacques Ph.D. 1957 Brown

Eshel, Nachman Ph.D. 1965 CUNY

Forray, Martin Ph.D. 1955 C. W. Post

Fox, Edward Ph.D. 1958 RPI

Gazis, Denas Ph.D. 1957 IBM

Gong, Chung DES 1970 Ebsco

Goodman, Lawrence Ph.D. 1949 Univ. of Minnesota

Haines, Daniel Ph.D. 1968 Univ. of South Carolina

Hoppmann, W. H. Ph.D. 1947 Univ. of South Carolina

Huang, Y. T. Ph.D. 1961 Huang & Associate

Kane, Thomas R. Ph.D. 1953 Stanford

Kaul, Raj Ph.D. 1963 SUNY Buffalo

Lee, Peter C. Y. DES 1963 Princeton

Lubkin, J. L. Ph.D. 1964 Michigan State

Lubowe, Anthony DES 1961 Bell Labs

McNiven, Hugh Ph.D. 1958 Berkeley

McCoy, John Catholic Univ.

Mediek, Mathew Ph.D. 1957 Michigan State

Newman, E. G. IBM

Pao, Yih-Hsing Ph.D. 1959 Cornell, Zhejiang University

Robinston, Kenneth ITEK Corp.

Rongved, Leif Ph.D. 1953 Bell Labs

Schwartz, Jeremy DES 1969 Naval Weapons Lab

Tasi, James Ph.D. 1961 SUNY Stony Brook

Tiersten, Harry Ph.D. 1961 RPI

VI. TREND IN CHINA (RESONATORS AND OSCILLATORS)

Quartz is the most widely used material for piezoelectric resonators. The production of quartz material and devices in China has been increasing rapidly.^[23]

(i) 1990: 0.12 billion pieces of crystals.

(ii) 2003: 2.8 billion pieces, 2000 ton quartz material, 300 companies. Export: \$530 million, Import: \$980 million (high-level comp.)

Overall China exports a considerable amount of materials or crystal chips and lower-level components at low prices, and imports a relatively smaller amount of high-level components at relatively higher prices.

VII. CONCLUSIONS

There are many challenging mechanics problems in the UFFC-S piezoelectricity research. Mechanics involvement is essentially limited to Mindlin's school which since the 1950s has been playing a central role in theoretical research of piezoelectricity in the UFFC-S. More mechanics participation is needed. It is hoped that this paper will help bridge the gap between the mechanics community and the UFFC-S on piezoelectricity research.

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